PREFACE

The emergence of optoelectrochemical sensing devices provides simple, rapid, cost-effective method for the disease diagnosis in comparison to the traditional techniques. Surface engineering plays a major role in development of high-performance optoelectrochemical biosensors, as it directly influences sensitivity, selectivity, and stability. The various surface modification techniques enhance electrode interfaces for improved bio-recognition and signal transduction. Key approaches include self-assembled monolayers, nanostructured coatings, chemical functionalization, and plasma treatments, each tailored to optimize surface properties such as roughness, hydrophilicity, and charge distribution. Nanomaterials, including metal nanoparticles, graphene, and carbon nanotubes, play a crucial role in improving electron transfer kinetics and light-matter interactions, thereby boosting sensor performance. Additionally, biomimetic modifications, such as peptide or polymer-based coatings, facilitate selective molecular recognition, reducing non-specific interactions. The synergy between optical and electrochemical transduction mechanisms is further enhanced through engineered plasmonic and photoactive surfaces, enabling real-time, label-free detection with ultra-low detection limits. Recent advancements in hybrid nanomaterials and multifunctional interfaces open new pathways for developing next-generation biosensors with enhanced miniaturization, portability, and multiplexing capabilities. By integrating surface modifications with innovative material designs, we thought of developing simple, cost-effective opto-electrochemical devices for the diagnosis of chronic kidney disease (CKD) by targeting two different biomarkers. CKD is emerging as one of the major causes of the increase in mortality rate and is expected to become 5th major cause by 2050. Many studies have shown that it is majorly related to various risk factors, and thus becoming one of the major health issues around the globe. Early detection of renal disease lowers the overall burden of disease by preventing individuals from developing kidney impairment. Therefore, diagnosis and prevention of CKD are becoming the major challenges, and in this situation, biosensors have emerged as one of the best possible solutions.

Hence, we have designed our study in four different sections, where in the first part; we have developed a paper-based optical micro device for the detection of creatinine which helps in diagnosis of kidney disease. Creatinine is one of the most common and specific biomarkers for renal diseases, usually found in the physiological fluids. Its level is extremely important and critical to know not only in the case of renal diseases, but also in various other pathological conditions. Hence, the detection of creatinine in clinically relevant ranges in a simplistic and personalized manner is interesting and has great importance. In this direction, we have developed an optical platform for simple and point-of-care detection of creatinine. The developed biosensor was able to detect creatinine quantitatively based on selective optical signals. The sensor has been integrated with a smartphone to develop a palm-sized device for creatinine analysis in personalized settings. The sensor has been developed following facile chemical modification steps to anchor the creatinine selective antibody to fabricate a sensing probe. The fabricated sensor has been thoroughly characterized by FTIR, AFM, and controlled optical analyses. Creatinine in standard as well as in serum samples was analyzed following a chemical reaction that generates selective and sensitive optical signatures. The difference in color intensity and creatinine concentrations show an excellent dose-dependent correlation in the range of 5-400 μM, with a detection limit of 0.014 μM. Several interfering molecules, such as; albumin, glucose, ascorbic acid, citric acid, glycine, uric acid, Na^+, K^+, and Cl^-, have been tested using the biosensor, where no cross-reactivity was observed. The utility of the developed system to quantify creatinine in serum samples has also been validated and the obtained percentage recoveries lie within the range of 92-98%. The fabricated biosensor was found to be highly reproducible, and stable that retains its original signal for up to 28 days.

In the next section, we have designed and developed a 3D cascade-based paper microchip for the monitoring of human serum albumin (ALB) for the diagnosis of kidney disease. The paper surface has initially been chemically activated and antibodies specific to target biomarker are immobilized on the surface. Every step after modification has been characterized by FTIR, XPS, SPM and optical analysis. Further, the device model has been designed using CAD file, and a 3-D cascade device is fabricated with in-built constant light source to provide proper and controlled environment for in-situ image analysis. After adding the sample on the bioengineered paper, the antigen-antibody reaction takes place, after that addition of dye results in change of color from yellow to blueish-green within 40 sec. An optical method has been deployed for the analysis of the images by recognizing the specific area and the color intensity. Additionally, the immunosensor specificity has also been evaluated on a number of molecules that are usually found in the serum sample. The linear dynamic range of the developed immunosensor has been reported as 1-60 mg/mL, covering the normal as well as clinical range of ALB in physiological samples with a detection limit of 0.049(±0.002) mg/mL. With good precision and recovery, the device is able to successfully determine the ALB concentrations in serum sample. The developed device has simple and user-friendly interface and it may also help diagnosing CKD in personalized settings.

Further, in the third study we have tried to develop a software integrated electrochemical platform for the monitoring of creatinine in serum samples. It is a key biomarker for assessing the kidneys' normal functioning is creatinine, which is filtered out from the blood by the kidney. Thus, timely and specific detection of creatinine becomes necessary for diagnosis and subsequent treatment of kidney diseases. A field-deployable, software-integrated immunosensor for the detection of creatinine in serum sample has been developed. The immunosensor is fabricated by incorporating gold nanoparticles, boron doped MXene, polyaniline, and anti-creatinine antibody using an appropriate bioconjugation reaction. The developed sensor has been able to detect creatinine in a linear dynamic range of 10 nM to 0.1 M with a limit of detection of 1.72 (±0.07) nM. The sensor is also integrated with an indigenously developed software named 'CretCheck' which simplifies the process of data analysis. The software integrated personalized biosensing device can be used to find the creatinine concentrations directly from the obtained analytical signals. The developed immunosensor with the integrated software can also be implemented directly in primary health care facilities for creatinine detection in future.

In the final work, we have incorporated the cobalt metal organic framework (Co-MOF) for the development of electrochemical immunosensing platform for the detection of ALB. Co-MOF, also called Zeolite Imidazole Framework (ZIF-67), a subclass of MOF, is a burgeoning class of crystalline materials that features high porosity, large surface areas, remarkable stability, and flexibility. A coordination bond between an organic linker and a redox-active cobalt metal center forms ZIF-67 MOF, which has a unique architecture resembling zeolites. However, ZIF-67's limited conductivity impedes its application for electrochemical sensing. Considering this, we have been designed Co-MOF-carboxylated multiwalled carbon nanotubes (c-MWCNT) nanohybrid, which was further functionalized with an anti-ALB antibody to enable the selective electrochemical evaluation of ALB, a clinically proven kidney biomarker. ALB, the most prevalent protein secreted by hepatocytic cells, performs a number of essential bodily functions; however, a deviation from a normal level is prognostic of kidney failure and other illnesses. Several physical and electrochemical methods have been utilized to thoroughly characterize the developed immunosensing device. Following that, electrochemical impedance spectroscopy (EIS) has been employed to evaluate its efficacy, and the linearity and detection limit are estimated as 0.1 - 60 mg/mL and 0.024 mg/mL, respectively. These remarkable outcomes are the result of c-MWCNT and Co-MOF synergistic effects, and they present a cutting-edge approach for point-of-care ALB detection using composite materials based on MOFs.